Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-50-TR-2003/057 December 2003

Hydromechanics Directorate

Technical Report

The Effect of Scale on Propeller Tip-Vortex Cavitation Noise

by

Young T. Shen
Murray Strasberg

NSWCCD-50-TR-2003/057 The Effect of Scale on Propeller Tip-Vortex Cavitation Noise

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 2003	Final, December 2003

4. TITLE AND SUBTITLE
The Effect of Scale on Propeller Tip-Vortex Cavitation Noise

5. FUNDING NUMBERS
Sponsor Order:

Appropriation:
Subhead:
Program Element:
JO: 03-1-5080-262-50

6. AUTHOR(S)
Young T. Shen and Murray Strasberg

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Propulsion and Fluid Systems Department, Code 5400
NSWC, Carderock Division
9500 MacArthur Blvd.
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-50-TR-2003/057

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Sea Systems Command (NAVSEA)
Advanced Submarine Technology Office
93R

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12.a DISTRIBUTION / AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

12.b DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Measurements made long ago of the underwater noise associated with propeller tip-vortex cavitation on a submerged WWII submarine underway at sea, combined with measurements of the noise from a geometrically scaled model of the same submarine running submerged and self propelled in our towing basin, are used to calculate the value of the exponent in McCormick's equation, $(\sigma_F/\sigma_M) = (Re_F/Re_M)^n$, relating the ratio of full-scale to model cavitations numbers at cavitation inception to the ratio of the Reynolds numbers. The value of n is calculated to be 0.28, which is smaller than the usually assumed values ranging from 0.3 to 0.4. This provides evidence that n is not a constant, but decreases with increasing Reynolds number.

16. SUBJECT TERMS
Tip vortex cavitation; propeller cavitation noise; scale effect; cavitation

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

CONTENTS

FIGURES

TABLES

NOTATION

C	Blade chord length
L	Noise level in dB
L_{amb}	Ambient background noise level
L_{max}	Maximum noise level, noise level at the top of the S-curve
L_L	Noise level at the bottom of the S-curve
L_{-20}	20 dB below the maximum noise level
N	Propeller rotational speed
Po	Reference pressure
Pv	Vapor pressure of water
Re	Reynolds number based on chord and speed at 0.9-propeller radius
R_p	Propeller radius
V	Ship speed
V_r	Resultant speed at 0.9 propeller radius
σ	Cavitation number
∇	Differential of noise level between top and bottom of the S-curve
ρ	Water density
ν	Kinematic viscosity of water

SUBSCRIPTS

f	Full Scale
m	Model
max	Maximum
min	Minimum

ABSTRACT

Measurements made long ago of the underwater noise associated with propeller tip-vortex cavitation on a submerged WWII submarine underway at sea, combined with measurements of the noise from a geometrically scaled model of the same submarine running submerged and self propelled in our towing basin, are used to calculate the value of the exponent in McCormick's equation, $(\sigma_F/\sigma_M) = (Re_F/Re_M)^n$, relating the ratio of full-scale to model cavitations numbers at cavitation inception to the ratio of the Reynolds numbers. The value of n is calculated to be 0.28, which is smaller than the usually assumed values ranging from 0.3 to 0.4. This provides evidence that n is not a constant, but decreases with increasing Reynolds number.

ADMINISTRATIVE INFORMATION

This work was supported by NAVSEA 073RT under the direction of Meg Stout, Jude Brown and Richard Meyer. Job order number is 031-5080-262-50.

INTRODUCTION

Although propeller cavitation noise had been observed long before World War II [Wood, 1930], the underwater noise associated with cavitation in the tip vortices shed by submarine propellers became of interest to the navy during that war period. Ever since then, however, attempts to predict the onset and characteristics of cavitation noise of full-size ship propellers based on measurements made with model propellers in laboratory facilities have been plagued by uncertainty because of the well-known viscous scale effect on the onset of cavitation. Non-viscous hydrodynamics predicts that the cavitation number of the flow at cavitation onset should be independent of the size of the cavitating body, but the observed onset of propeller tip-vortex cavitation on a full-size propeller may actually occur at as much as twice the cavitation number observed on a small geometrically similar model. It is now customary to assume, as first proposed by McCormick [1954, 1962], that the ratio of full-scale to model cavitation numbers at cavitation onset should equal the ratio of the Reynolds numbers of the two flows raised to a power of about 0.35. Recently, however, Shen et. al. [Shen et al, 2003], have suggested that the exponent is not a constant, but should decrease with increasing Reynolds number.

Unfortunately, there is a paucity of published data to confirm the validity of Shen et. al.'s suggestion for Reynolds numbers of a full-size ship propeller. However, a data set providing a comparison of full-scale and model data was published by Strasberg [1977] some years ago, although not used then for the present purpose. The data set provides a comparison of noise levels measured in the 1940s of the underwater noise generated by tip-vortex cavitation on the propellers of a WWII submarine, running submerged at sea, with noise levels of a geometrically scaled model of the same submarine hull and propeller running submerged and self-propelled in our high-speed towing basin. This data set will be used in the present report to determine the ratio of full-scale to model cavitation numbers for the same cavitation condition.

CRITERIA FOR COMPARABLE CAVITATION CONDITION

The comparison will be based on the observed variation of the cavitation noise level with speed. Previous comparison criteria, which attempt to define a so-called *onset of cavitation* as either the speed at which cavitation bubbles are first observed *visually*, or the speed at which a specified number of *noise spikes* are observed on an oscillograph, or the speed at which the measured noise level exceeds the ambient background level by three dB or some other arbitrary number of dB, will not be used here. Instead, the comparison will be based on the speed at which the cavitation noise level in a wide, high-frequency band is a specified number of dB, say 15 or 20 dB, below the maximum observed level at higher speeds. This condition will be called *well-developed cavitation.* Determining the ratio of full-scale to model cavitation numbers at the condition of *well-developed cavitation*, as defined here, rather than at the so-called cavitation onset, is believed to have the following advantages:

(1) The onset of cavitation is subject to variability because of its sensitivity to the temperature of the water and its nuclei and gas content. On the other hand, these variables have relatively little effect on the noise once cavitation is well developed.

(2) Equipment for full-scale visual observation of propeller cavitation is difficult to provide, and observing the onset is subject to variability, often varying from one propeller blade to another.

(3) Defining cavitation inception in terms of the number of dB the noise level rises above the ambient background level, or the number of observed noise spikes, is subject to variability because it is dependent on the background noise level, which may vary considerably from one test environment to another, as subsequently discussed in detail.

(4) On the other hand, defining model and full-scale *well-developed cavitation* as corresponding to noise levels the same specified number of dB below the model and full-scale maximum levels, results in a comparison relatively independent of the acoustic characteristics of the environment.

TEST SET-UP

Full-scale: USS HAKE (SS256) was a four-bladed twin-screw submarine of the 212 class. The propeller diameters were 8.21 feet. Fig 1 provides qualitative information on the outline of blade profile, pitch distribution and the maximum thickness distribution. To ease the reading of this report, a brief discussion of the test set-up is given here. A detailed discussion of the test apparatus and data acquisition procedure is referred to Strasberg's reports [1944,1946].

Four hydrophones were installed 3 feet out from the hull at various distances from the propellers, as shown in Fig 2. One was placed on the port side directly above the propeller disk and approximately 8 feet from the shaft, one on the starboard side in the same relative position, and the other two forward and aft of the propeller on the starboard side. The hydrophones were supported by faired struts welded to the hull, one of which is shown in Fig 3. The cables were run along the outside hull through 1-inch pipes and thence through stuffing boxes into the after torpedo room where the measuring instruments were located. The hydrophones were calibrated a total of five times before and after these tests. The hydrophone calibration curve, noise level measuring devices, and frequency analyzer are given in Strasberg's reports.

The procedure in the sea tests was to submerge to the desired depth and run through a series of speeds at that depth, starting with the lowest speed. A run at one speed took about 10 minutes, which provided sufficient time for continuous frequency analyses and other measurements. The two propeller shafts were rotated at the same speed. The depths tested were at surface, and submergence 55 feet and 100 feet. The submergence refers to the depth of the propeller shaft below the water surface. Only data for the submerged runs are analyzed and discussed in this report.

Model: The model tests were carried out in our high-speed towing basin, using a 20-feet wooden model (hull model 3803) of the SS-212 fleet submarine. The model propeller diameter was 0.566 feet with the geometric linear scale ratio of 14.5. The model hull was attached to the towing carriage by a streamlined strut and submerged 3 feet below the water surface. The carriage was specially designed to be quiet, being driven by an electric motor and rubber-tired wheels. Although the fleet submarine was driven by two propellers, only one model propeller was installed for these measurements. The propeller rotation speed was adjusted to simulate self-propelled conditions, using an advanced ratio determined from speed trials of the prototype submarine. The noise measurements were made with a small hydrophone placed inside the model hull with its sensitive element projecting downward into the water below the keel 1.33 feet forward of the propeller.

CAVITATION NOISE MEASUREMENTS

Full-scale: Fig 4 shows two curves of the full-scale noise level in various speeds at depths of submergence of 55 ft and 100 ft, respectively. The absolute noise levels given for the frequency band extending from 10 to 30 kHz are based on a root-mean-square average of the filter response and the normal–incidence-sensitivity of the hydrophone in the band. Both curves show that the propeller had a quiet speed range and a noisy speed range. At the noisy speed range, the noise level increased very rapidly with speed. After this sudden increase, further increase in speed caused little additional change in level with the speed. In short, the noise level exhibits an integral $\int$ shape or stretched S-shape.

Let L_{Maxf} = 131 dB as shown in Fig 4 denote the noise level at the top of the stretched S-curve. Let L_{Lf} = 77 dB denote the noise level at the bottom of the S-curve, namely at the junction point of the noisy speed range and quiet speed range. The subscript f denotes the full-scale data. It is noted that L_{Lf} can be influenced by the full-scale background noise, whereas the effect of background noise on L_{Maxf} is negligible. This fact will be utilized in the following analysis. Also denote the difference in noise levels between L_{Maxf} and L_{Lf} by ∇_f, namely

$$\nabla_f \equiv L_{Maxf} - L_{Lf} = 54 \text{ dB} \qquad (1)$$

Model: Fig 5 shows a curve of the model noise level measured in a high speed-towing basin at various carriage speeds and at a depth of submergence of 3 feet. The absolute noise level was given for the frequency band extending from 10 to 100 kHz. Again, the noise level is based on a root-mean-square average of the filter response. To incorporate the scale effect on acoustic spectra between full-scale and model, the frequency band for the model covers a wider range of 10 to 100 kHz in the model.

The curve shows that the model propeller also had a quiet speed range and a noisy speed range. Again, at the noisy speed range, the noise level increased very rapidly with the speed. After this sudden increase, further increase in speed caused little additional change in level with the speeds. In short, the model propeller noise level also exhibits a stretched S-shape.

The noise level at the top of the S-curve is $L_{Maxm} = 113$ dB. The noise level at the junction point of the noisy speed range and quiet speed range is $L_{Lm} = 80$ dB. The subscript m denotes the model data. It is noted that L_{Lm} is strongly influenced by the background noise, while L_{Maxm} is not. The difference in noise levels between L_{Maxm} and L_{Lm} is given by

$$\nabla_m \equiv L_{Maxm} - L_{Lm} = 33 \text{ dB} \tag{2}$$

In an ideal case if cavitation patterns occurring in model and full-scale are similar, the values of ∇_m and ∇_f are expected to be equal. However, the difference between the cavitation noise and background noise levels is smaller for the model than for the full-scale. Due to the effect of background noise, ∇_m in model was 21 (= 54 –33) dB less than ∇_f in full scale. This result implies that when cavitation was first detected in the model, the cavitation was already more developed than the cavitation first detected in full-scale. Recall that the objective of this study is to estimate the effect of Reynolds number on propeller cavitation noise. The effect of background noise on propeller noise, which is not directly related to the Reynolds number, must be removed from the analysis. In this respect, we will apply similarity flow approach to formulate the noise scaling problem as the one introduced in the previous work by Shen at al [2003]. For this we consider the following analysis.

REYNOLDS NUMBER EFFECT ON PROPELLER NOISE DUE TO A WELL-DEVELOPED CAVITY

Consider as an example the full-scale trial run at 55 feet submergence with a noise level of 111 dB, which was 20 dB below maximum. This noise level was well above the background noise level, which implied that this propeller noise was due to a well-developed tip vortex cavity. The noise level of 111 dB is denoted by L_{-20f}

$$L_{-20f} = L_{Maxf} - 20 \text{ dB} \tag{3}$$

From Figure 4, the noise level of 111 dB occurred at the ship speed of $V_f = 4.7$ knots and $N_f = 94$ RPM. We obtain the cavitation number σ_f by

$$\sigma_f = (P_0 - P_v) / (0.5\, \rho V_f^2) = 88.9 \tag{4}$$

where P_0 and P_v denote the reference pressure and vapor pressure, respectively. The resultant velocity, V_{rf} at 0.9 propeller radius, R_p is

$$V_{rf} = \sqrt{V_f^2 + [0.9 R_{pf} N_f^2 / 60]^2} = 37.2 \text{ ft/sec} \tag{5}$$

The Reynolds number based on the chord length of 1.65 ft at 0.9 R_p is

$$Re_f = V_{rf} * C_f / \upsilon_f = 5.54 \times 10^6 \qquad \text{at } 70^\circ\text{F} \tag{6}$$

Next, consider the model data at the noise level of 20 dB below the maximum at depth of submergence of 3 ft.

$$L_{-20m} = L_{Maxm} - 20 \text{ dB} \tag{7}$$

From Figure 5, this noise level occurred at the carriage speed of V_m = 4.4 knots and N_m=1268 RPM. We obtain $\sigma_m = 41.9$, V_{rm} = 34.9 ft/sec, and $Re_m = 3.78 \times 10^5$ at 70°F.

Recall that the cavitation pattern on the full-scale propeller at L_{-20f} was expected to be similar to the cavitation pattern on model propeller at L_{-20m}. According to the classic cavitation scaling, similar cavitation patterns occurring in full-scale and model should occur at the same value of cavitation number. The above calculations give σ_f = 87.6 while σ_m = 41.85. The difference in the values of cavitation numbers at the same cavitation pattern is due to Reynolds number effect.

Let scale effect on propeller cavitation inception be expressed by

$$\sigma_f / \sigma_m = (R_{ef} / R_{em})^n, \tag{8}$$

Then the Reynolds number effect on propeller cavitation noise can be obtained by

$$n = \text{Log} (\sigma_f / \sigma_m) / \text{Log} (Re_f / Re_m)$$

$$= \text{Log} (88.9 / 41.9) / \text{Log} (5.54 \times 10^6 / 3.78 \times 10^5) = 0.28 \tag{9}$$

The value of n = 0.28 represents the Reynolds number effect on propeller cavitation noise at 20 dB below the maximum noise levels of full-scale and model. Note that background noise has negligible effect on cavitation noise at this stage of well-developed cavities.

In the classic approach, it often uses cavitation inception speed and the corresponding noise as the base to characterize the effect of cavitation on the intensity of noise with developed cavities. The problem with this approach is that to define cavitation inception speed is subjective to the background noise dependency. This problem is avoided in the present approach by using the speed corresponding to the maximum cavitation noise as the base. By using the similarity flow approach, scale effect on propeller noise due to tip vortex cavitation can be derived.

Ship speeds and cavitation noise measured in full-scale trials are shown in Fig 6 for the submergence depths of 55 ft and 100 ft, respectively. The x-axis denotes the differential of noise level ∇dB from the maximum noise level L_{Maxf}. Note that the actual noise level at $L_{-\nabla dB}$ can be computed from $L_{-\nabla dB} = L_{Maxf} - \nabla dB$. The vertical axis denotes the ship speed, which is obtained from Fig 4. The juncture of cavitation noise and background noise occurred around 77 dB. Namely background noise is 54 dB below the maximum noise.

Ship speeds and cavitation noise measured in the towing tank are shown in Fig 7. The juncture of cavitation noise and background noise occurred around 80 dB. Namely background noise is 33 dB below the maximum noise. A comparison of model tests shown in Fig 7 and full-scale trial data shown in Fig 6 suggests that the background noise in the model tests is 21 dB too high.

SCALE EFFECT ON PROPELLER NOISE DUE TO DEVELOPED CAVITIES WITH SIMILAR CAVITATION PATTERNS

The approach presented in the previous section will now be extended to calculate the Reynolds number effect on propeller noise at various stages of tip vortex cavitation development. Tables 1 and 2 show the Reynolds number effect on propeller noise at various cavitation conditions for 55 feet and 100 feet submergence, respectively. In the full-scale case, the SPL at 50 dB below maximum was still above the background noise, namely the ship speeds associated with propeller cavitation noise was still detective acoustically to L_{-50}. On the other hand, the towing tank carriage speeds associated with propeller cavitation noise could be detected to L_{-30} due to background noise contamination. This explains why no model data are shown in Tables 1 and 2 for the noise levels of L_{-40} to L_{-50}.

Differential SPL from peak SPL is specified first and the corresponding ship and carriage speeds are obtained from Figs 4 and 5. The values of n are computed based on the method outlined above. In this approach, it is assumed that cavitation patterns were similar between full-scale and model when the differential noise levels L_{-dB} are the same. The Reynolds number effect on propeller noise shown in Tables 1 and 2 and is plotted in Fig 8. The values of n vary around 0.25 to 0.29 with majority in 0.28. It is concluded that under the similarity flow and cavitation assumptions, the scale effect on differential propeller noise due to tip vortex cavitation can be estimated in average by

$$\sigma_f / \sigma_m = (R_{ef} / R_{em})^n, \quad \text{and } n = 0.28$$

FULL-SCALE CAVITATION INCEPTION SPEED PREDICTION, A CASE STUDY

Given: Consider the acoustic data shown in Fig 4 measured at 55 ft depth of submergence. The juncture point of quiet and noisy data in this trial run occurred around 77 dB. Noise produced by the propeller cavitation is detectable or can degrade noise detection capability if the noise level is above 77 dB. For the purpose of this study, cavitation inception speed at 55 ft depth of submergence is defined to be when the noise level reaches at 80 dB. According to this definition, cavitation inception speed occurred at 3.95 knots as shown in Fig 4. This gives $\sigma_f = 125.8$, $V_{rf} = 31.29$ ft/sec, $R_{ef} = 4.66 * 10^6$.

Objective of this case study is to show the scale effect on full-scale cavitation inception speed prediction. Model data are given in Fig 5. By coincident, the juncture point of quiet and noisy data in this series of model tests occurred around 80 dB.

Example 1, consider a classic approach of using the model data of 3 dB above the background for full-scale prediction. From Fig 5, the carriage speed at 83 dB was 4.10 knots. This gives $\sigma_m = 49.9$, $V_{rm} = 32.5$ ft/sec, $R_{em} = 3.54 * 10^5$. From these data, we obtain

$$n = \text{Log}\,(\sigma_f / \sigma_m) / \text{Log}\,(Re_f / Re_m) = 0.36$$

This example shows that if model data at 3 dB above the background is used, a value of n = 0.36 would be calculated to predict the full-scale cavitation inception speed of 3.95 knots at 55 ft submergence (see Table 1). As noted in Table 2, a value of n = 0.44 would be calculated to predict full-scale cavitation inception spped at 100 ft submergence..

Example 2, consider another approach of using the model data at the juncture of quiet and noisy speeds, namely using the background model speed for full-scale prediction. From Fig 5, the carriage speed at 80 dB was 3.85 knots. This gives $\sigma_m = 54.9$, $V_{rm} = 30.5$ ft/sec, $R_{em} = 3.32 * 10^5$. From these data, we obtain

$$n = \text{Log}\,(\sigma_f / \sigma_m) / \text{Log}\,(Re_f / Re_m) = 0.315$$

This example shows that if model data at 0 dB above the background is used, a value of n = 0.315 would be calculated to predict the full-scale cavitation inception speed of 3.95 knots.

As pointed out in Figs 6 and 7, model background was 21 dB too high to have cavitation similarity between full-scale and model. Model cavitation at background noise level was more developed than full-scale cavitation at inception speed. A value of n = 0.315 would be calculated for full-scale cavitation inception speed prediction. Model cavitation at 3 db above the background level was even more developed than full-scale cavitation at inception speed. A value of n = 0.36 would be calculated for full-scale cavitation inception speed prediction. Hypothetically, if the background noise in the carriage tests could be reduced by 21 dB, similar cavitation patterns would be expected between full-scale and model and a value of n = 0.28 would be calculated to predict full-scale cavitation inception speed. However, this value is the only value that is relatively independent of the background noise. The other values are subject to errors.

FULL-SCALE AND MODEL DATA

Consider case (a) of propeller noise due to severe cavitation with similarity cavitation patterns between full-scale and model. One of the issues in acoustic measurements is the background to signal ratio. In the cases of heavy propeller cavitation, the effect of background on cavitation signal is small and negligible. If the cavitation patterns were similar between full-scale and model, Tables 1 and 2 show that the Reynolds number effect on full-scale and model propeller cavitation noise is around n = 0.27 to 0.29.

Case (b) of propeller noise due to well-developed cavity but dis-similar cavitation patterns between full-scale and model: Cavitation with the noise level of 3 dB above the background in model test was more developed than cavitation in full-scale at cavitation inception. If the classic approach of using 3 dB above the background is used to predict the full-scale cavitation inception speed, a value of n = 0.36 would be needed.

Case (c) of propeller noise due to less well-developed cavity but dissimilar cavitation patterns between full-scale and model: If the acoustic data at the background noise is used to predict full-scale cavitation inception speed, a value of n = 0.315 would be needed.

Study so far indicates that if the background in the carriage tests can be reduced by 21 dB, similar cavitation patterns are expected between full-scale and model. A value of n = 0.28 may provide adequate cavitation inception speed prediction. With the increase in background noise, cavitation inception prediction requires higher values of n.

CONCLUSIONS

Full-scale and model measurements showed that the propeller had a quiet speed range and a noisy speed range. The measured absolute noise level exhibits a stretched S shape.

Based on a similarity flow approach of having similar tip vortex cavitation patterns between full-scale and model, the relative increase in noise dB level due to development of cavity is the same between full-scale and model.

The background is found to be around 21 dB higher in model tests than full-scale measurements for having similar tip vortex cavitation patterns between full-scale and model.

The relative increase in noise dB level between full-scale and model is analyzed by using a classic method of $\sigma_f / \sigma_m = (R_{ef} / R_{em})^n$.

In well-developed cavities with similar cavitation patterns, the Reynolds number effect on propeller noise due to tip vortex cavitation is found to be around n = 0.28.

A study case was formulated to predict full-scale cavitation inception speed of 55-ft submergence from model test. In well-developed cavities but dissimilar cavitation patterns between full-scale and model, Reynolds number effect on full-scale cavitation inception speed prediction is found to be around n = 0.36 if model acoustic data of 3 dB above the background would be used and around n = 0.315 if model acoustic data at the background level would be used.

ACKNOWLEDGMENTS

We appreciate very much the support and technical discussions by Mr. Jude Brown. We thank Dr. S. Jessup, Mr. R. Etter and Dr. M. Wilson for their helpful discussions.

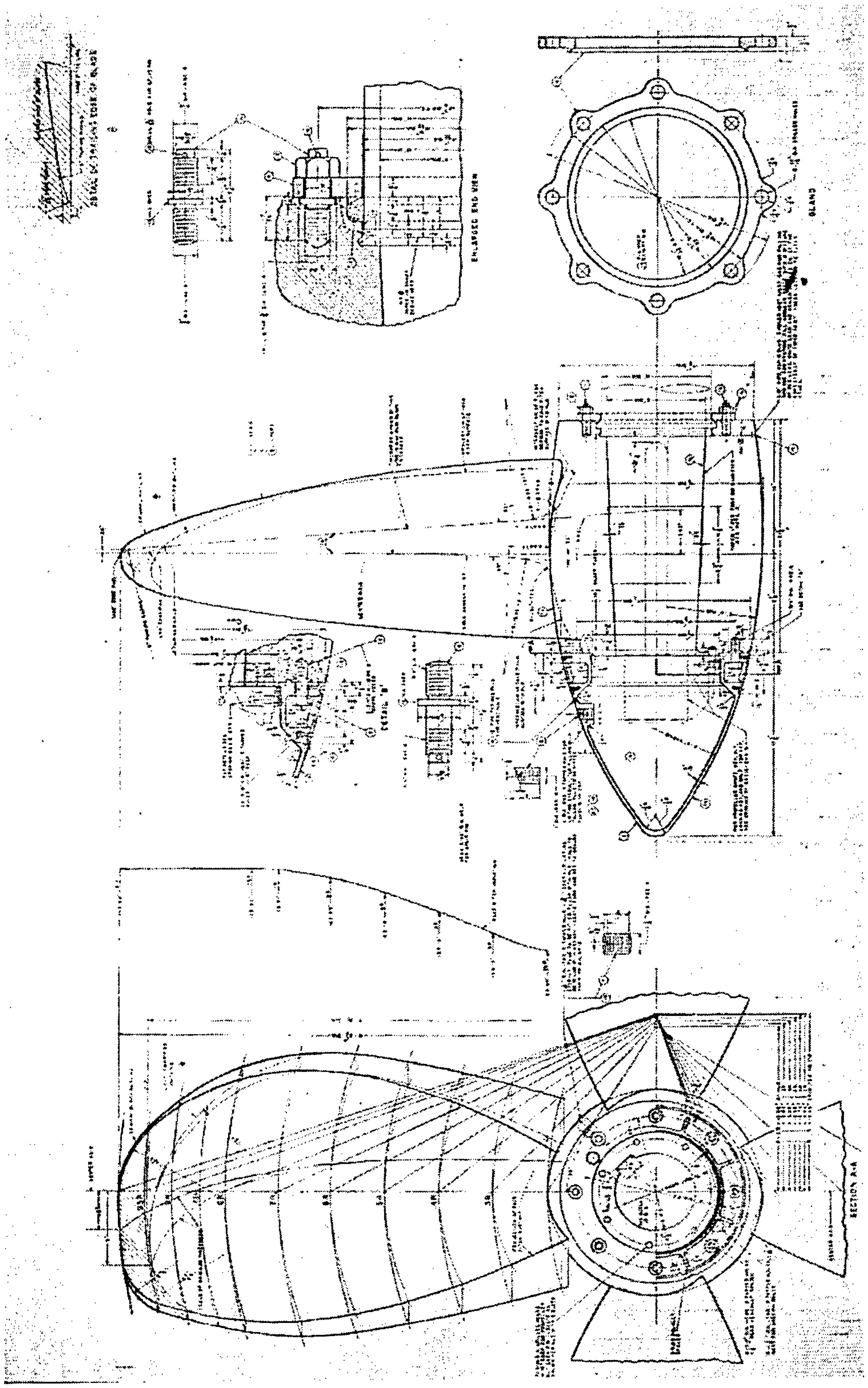

Fig. 1. Propeller blade outline of USS HAKE (SS256).

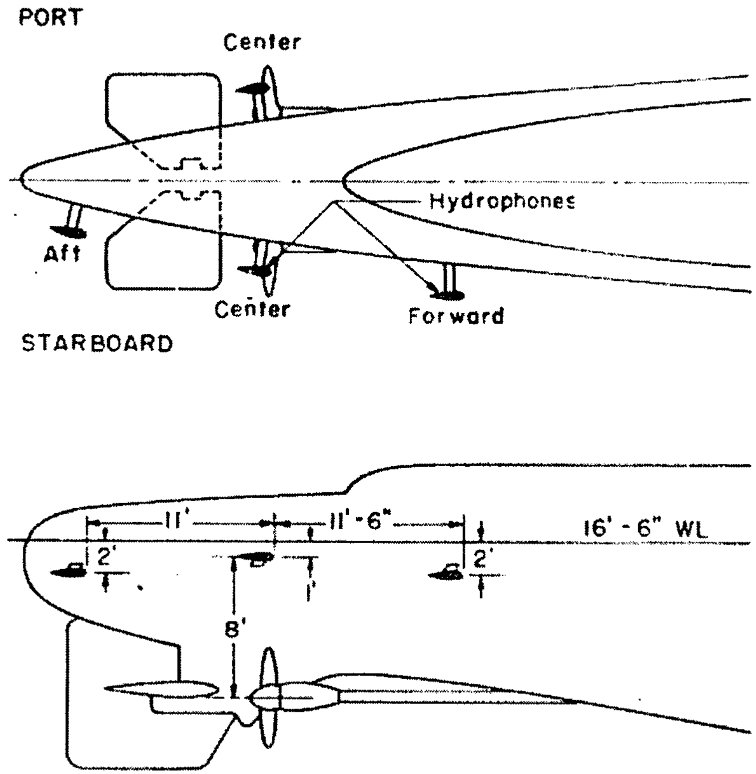

Fig. 2. Location of the hydrophones on the USS HAKE.

Fig. 3. Double-arm strut and hydrophone, with tail fairing.

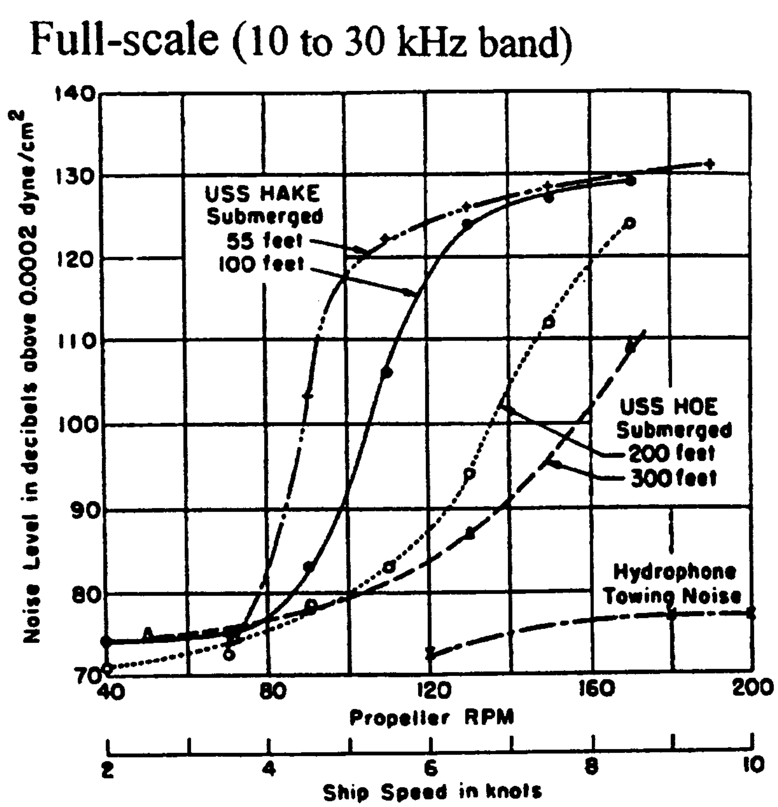

Fig. 4. Noise level measured at full scale.

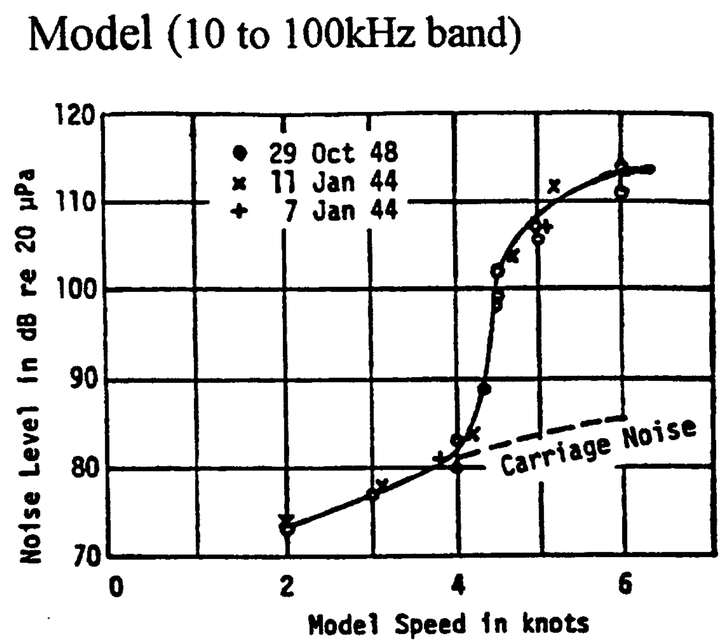

Fig. 5. Noise level measured at model.

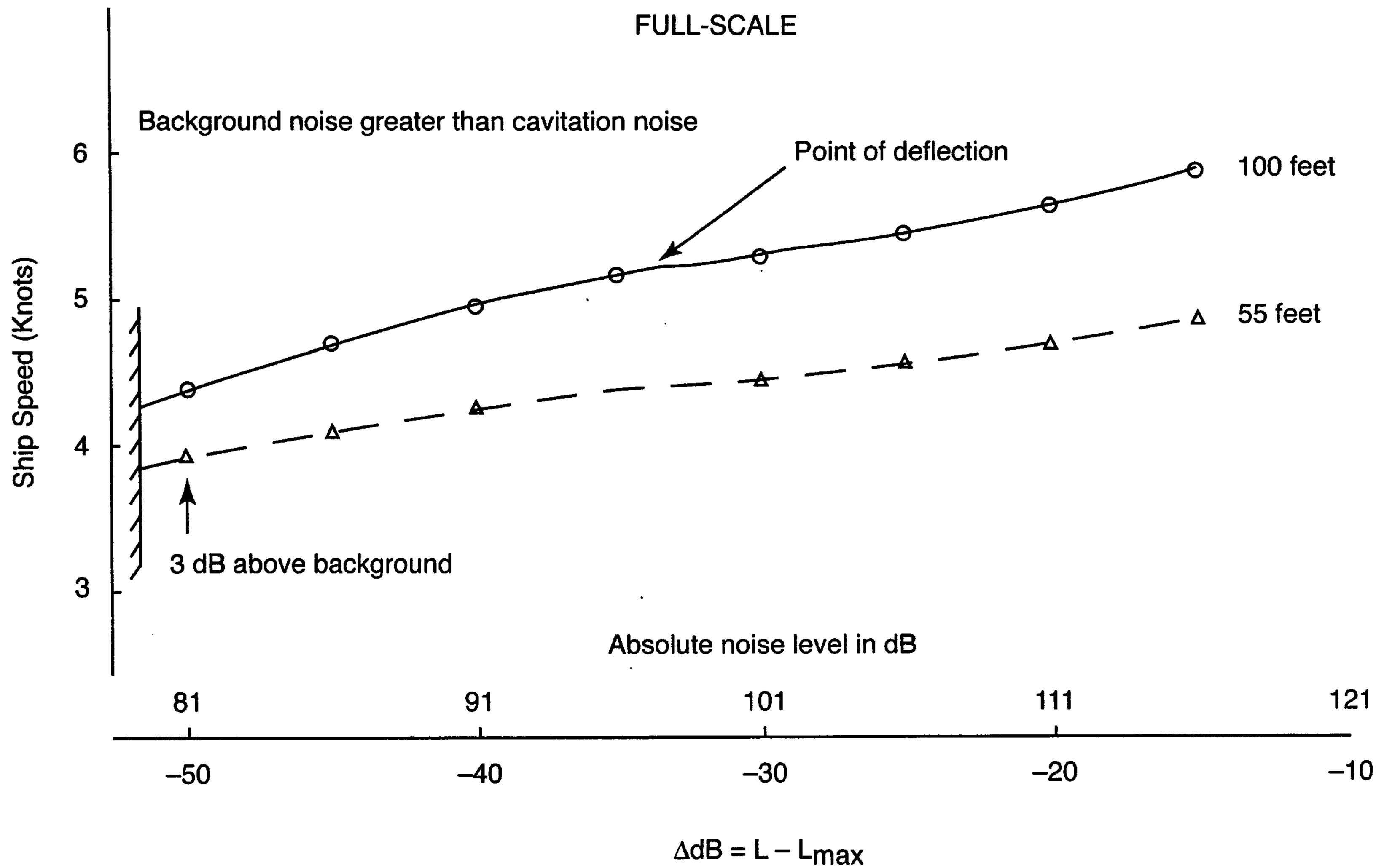

Fig. 6. Full-scale ship speed versus noise level due to tip vortex cavitation.

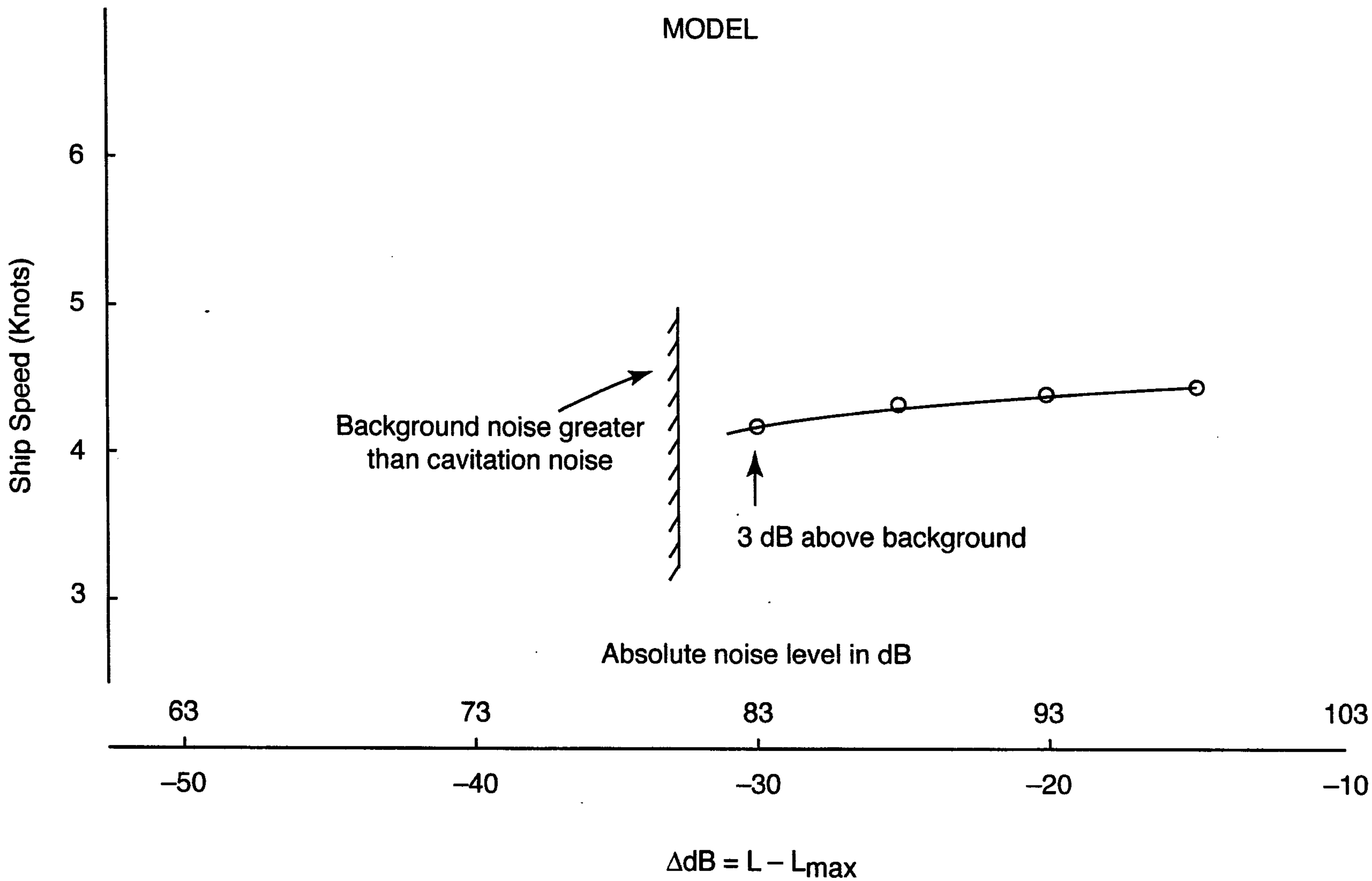

Fig. 7. Model ship speed versus noise level due to tip vortex cavitation.

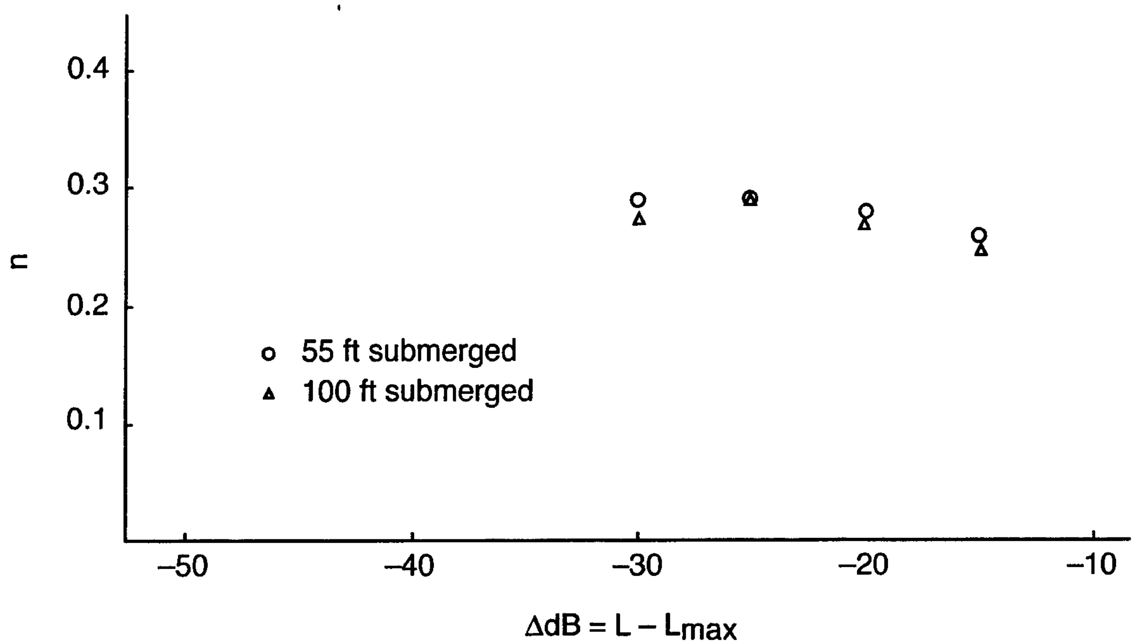

Fig. 8. The effect of Reynolds number on propeller cavitation noise scaling index.

Table 1: Reynolds Scale at Various Cavitation Conditions
for 55-Feet Full-Scale Submergence

(Model Submergence, 3ft)

Differential SPL From Peak SPL	Cavitation Speed		n
	Model	Full Scale	
L_{amb} +3 dB	4.1	3.95	0.36
L_{max} –50 dB	—	4.0	
L_{max} –45 dB	—	4.1	—
L_{max} –40 dB	—	4.25	
L_{max} –35 dB	—	4.35	
L_{max} –30 dB	4.15	4.45	0.29
L_{max} –25 dB	4.3	4.55	0.29
L_{max} –20 dB	4.4	4.7	0.28
L_{max} –15 dB	4.45	4.9	0.26

Table 2: Reynolds Scale at Various Cavitation Conditions
for 100-Feet Full-Scale Submergence

(Model Submergence, 3 ft)

Differential SPL From Peak SPL	Cavitation Speed		n
	Model	Full-scale	
L_{amb} +3 dB	4.1	4.3	0.44
L_{max} –50 dB	—	4.4	—
L_{max} –45 dB	—	4.7	—
L_{max} –40 dB	—	4.95	
L_{max} –35 dB	—	5.2	
L_{max} –30 dB	4.15	5.3	0.28
L_{max} –25 dB	4.3	5.55	0.29
L_{max} –20 dB	4.4	5.7	0.27
$_{max}$ –15 dB	4.45	5.9	0.25

REFERENCES

Fruman D. et al , 1994, "Tip vortex roll-up and cavitation," 19th Symposium of Naval Hydrodynamics, ONR, Wash. DC

McCormick, B.W. 1954, "A Study of the Minimum Pressure in a Trailing Vortex System," PhD Dissertation, Penn State University

McCormick, B.W. 1962, "On Cavitation Produced by a Vortex trailing from a Lifting Surface," J. of Basic Eng.

Shen Y. T., S. Jessup, and S. Gowing 2003, "Tip vortex cavitation inception scaling for high Reynolds number application," 4th ASME-JSME Joint Fluids Engineering Conference, Honolulu, HI. July 6-11

Strasberg, M. and W. J. Sette, 1944, "Measurements of propeller noise on three submarines of the SS212 Class," DTMB Report 1944, Declassified NSEDC 5511, 1975

Strasberg, M., 1946, "The development of cavitation noise by model propellers," DTMB Report 543, Declassified by NSRDC 561:CEB 5605

Strasberg, M., 1977, "Propeller cavitation noise after 35 years of study," Proc. ASME Symposium on Noise and Fluids Engineering, Atlanta, Ga.

Wood A. B., 1930, *Text Book of Sound*, The Macmillan Co., N.Y., p. 230; also G. Bell & Sons Ltd., London (1957); p. 215.

INITIAL DISTRIBUTION

EXTERNAL DISTRIBUTION

Organization	Name	Copies
NAVSEA		
SUB-RT	Stout, M.	1
ONR		
333	Kim, K.	1
333	Purtell, P.	1
Dynaflow, Inc.	Chahine, G.	1
	Hsiao C.	1
Mississippi State U.	Brewer W.	1
DTIC		2
Johns Hopkins U	Katz, J	1
PSU/ARL	Billet, M.	1
	Straka, W.	1
	Lauchley	1
U. of Michigan	Ceccio, S.	1
U. of Minnesota	Arndt, R.	1
Antion	Martinez	1

CENTER DISTRIBUTION

NSWCCD		
Code 3421	NSWCCD TIC	1
Code 50	Koh, I.	1
Code 506	Walden, D.	2
Code 5080	Brown, J.	1
	Cox, B.	1
	Meyer, R.	1
Code 5200	Day, W.	1
Code 5400	Chen, B.	1
	Etter, R.	1
	Gorski, J.	1
	Gowing, S.	1
	Jessup, S.	1
	Remmers, K.	1
	Shen, Y.	5
	Szwerc, R.	1
	Wilson, M.	1
Code 5500	Applebee, T.	1
Code 5600	Ammeen, E.	1
Code 70	Jebsen, G	1
Code 7051	Blake, W.	1
Code 701	Strasberg, M.	5
Code 725	Shang, P.	1
	Gonzales, J.	1
	Gershfeld, J	1
	Sevik, M.	1